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The Implications of Galaxy Formation Models for the TeV Observations of Current Detectors

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Abstract. This paper represents a step toward constraining galaxy formation models via TeV gamma ray observations. We use semi-analytic models of galaxy formation to predict a spectral distribution for the intergalactic infrared photon field, which in turn yields information about the absorption of TeV gamma rays from extra-galactic sources. By making predictions for integral flux observations at >200 GeV for several known EGRET sources, we directly compare our models with current observational upper limits obtained by Whipple. In addition, our predictions may offer a guide to the observing programs for the current population of TeV gamma ray observatories.

INTRODUCTION

As shown previously [8,11], measurements of the extra-galactic background light (EBL) may be used to probe models of galaxy formation. The model predictions for the EBL can be probed indirectly via the attenuation of high energy gamma rays, due to pair production with the EBL photon field. The $\gamma\gamma \rightarrow e^+e^-$ cross section [5] is maximized when $E_\gamma E_{EBL} \sim 2m_e^2$. From this, we expect TeV gamma rays to be primarily absorbed by EBL photons in the infrared (IR) region of the spectrum. Galaxy formation models which differ in their predicted amount of infrared EBL

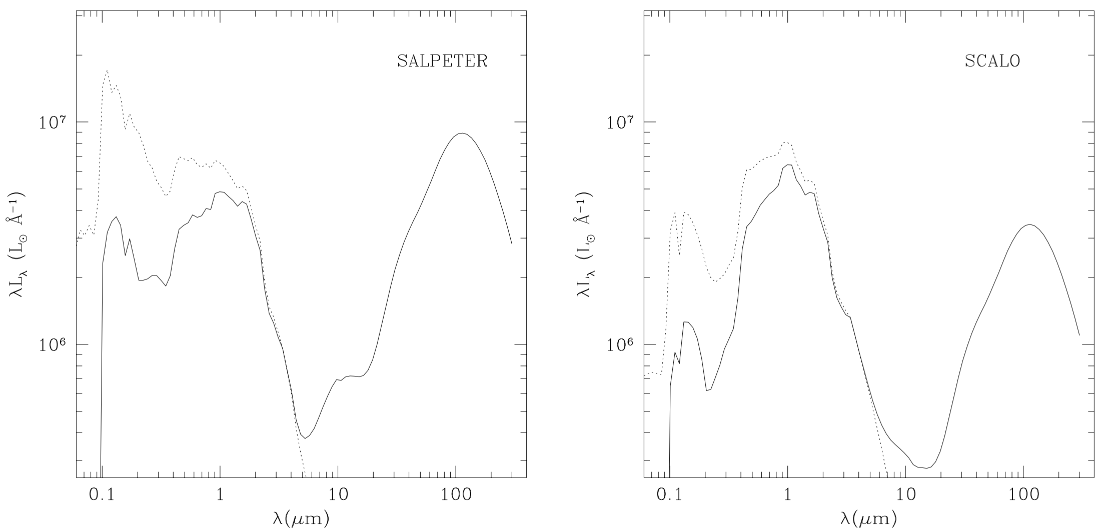

FIGURE 1. These figures represent the spectrum of an average "Milky Way" sized galaxy for each of the two IMFs considered here. The dotted lines indicate the starlight spectra without the effects of dust, while the solid lines represent the spectra with the effects of extinction and emission by dust.

should be distinguishable by their predicted TeV gamma ray absorption. Here we present results of simulations for the observed spectra of six candidate blazars, including the absorption corrected integral flux we would expect from two plausible galaxy formation models. Other work calculating EBL absorption of TeV spectra under somewhat different assumptions is presented in [12] and [9].

SEMI ANALYTIC MODELS

We have modeled the EBL using the semi-analytic models (SAMs) of galaxy formation discussed in [16], and a similar ΛCDM cosmology where $\Omega_\Lambda = .7$, $\Omega_m = 0.3$, and $h = 0.7$, normalized such that the rms mass variance on the scale 8 Mpc/h is 1.

We have modeled the EBL for our ΛCDM cosmology using two popular models of the stellar initial mass function (IMF): the Salpeter IMF [13] and the Scalo IMF [14]. The IMF, which describes the stellar mass distribution, affects the wavelength distribution of the starlight produced, and hence the wavelength distribution of the EBL.

The main difference between the two models is that the Salpeter IMF has a larger fraction of high-mass stars than Scalo, provided both are normalized to the same total mass of stars. Sample spectra for both models appear in Fig. 1. Note that the Salpeter IMF has more ultraviolet light than the corresponding Scalo model. This is because high-mass stars produce more ultraviolet light than low-mass stars. Furthermore, because dust absorbs ultraviolet light and emits around 100 μm,

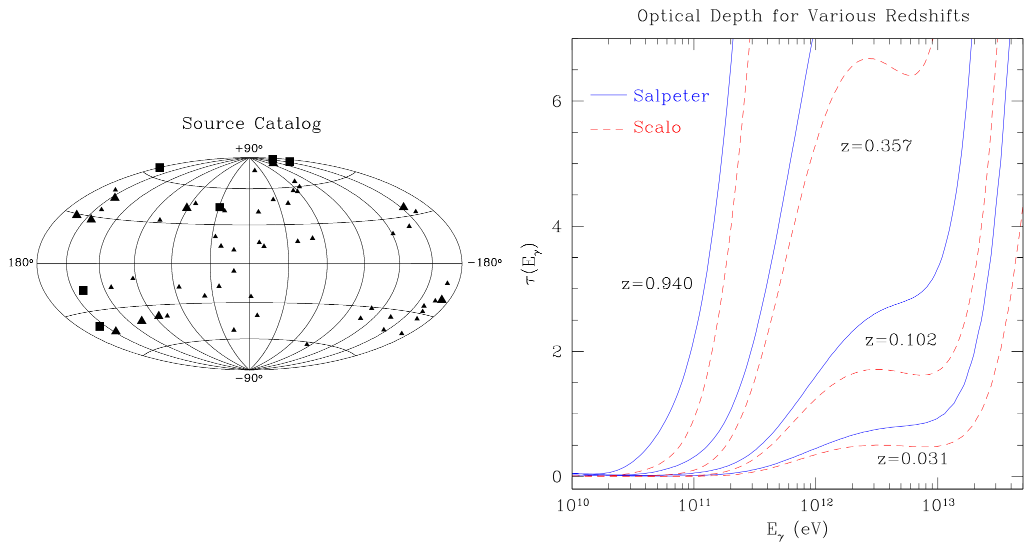

FIGURE 2. **a)** Source catalog in galactic coordinates. Small points denote all considered EGRET AGN, of which 16 (large points) were selected as "candidate" sources. We have plotted absorbed spectra for six of these candidate sources (large squares) **b)** Optical depth for selected redshifts as a function of gamma ray energy.

the additional ultraviolet light produced by the Salpeter IMF results in a greater amount of $\sim$100 μm EBL. Due to this enhanced 100 μm bump, the Salpeter IMF should produce stronger attenuation for corresponding gamma rays between about 10 GeV and 10 TeV.

IMPLICATIONS FOR TeV ASTRONOMY

We chose our candidate TeV sources from the third EGRET catalog [6]. Of the 67 AGN listed in that catalog, we considered a subset of 60 sources for which there was complete data. These sources are shown in Fig. 2a. Of the 60 sources considered, 16 were chosen as candidate sources for TeV observations based on the hardness of their spectra and their integral flux above 100 MeV. Candidate sources appear as large points in Fig. 2a. We then simulated the observed integral flux for six of these sources (large squares), both with and without absorption corrections. Of our six sources, one (Mrk421) is an X-ray selected BL Lac, one (4C+29.45) is a flat spectrum radio quasar, and the rest are radio selected BL Lacs.

For the absorption simulations, we assumed a simple power law for the intrinsic spectrum of each source. We did not assume any source absorption effects. Spectral indices and pre-factors for the differential spectra were obtained from the third EGRET catalog [6], and calculations of these differential spectra followed [17]. We then modified each of these intrinsic spectra with an absorption factor. We assumed the functional form of this factor to be an exponential decay, whose exponent (τ) is derived from the calculations of the EBL mentioned earlier. Plots of τ as a function

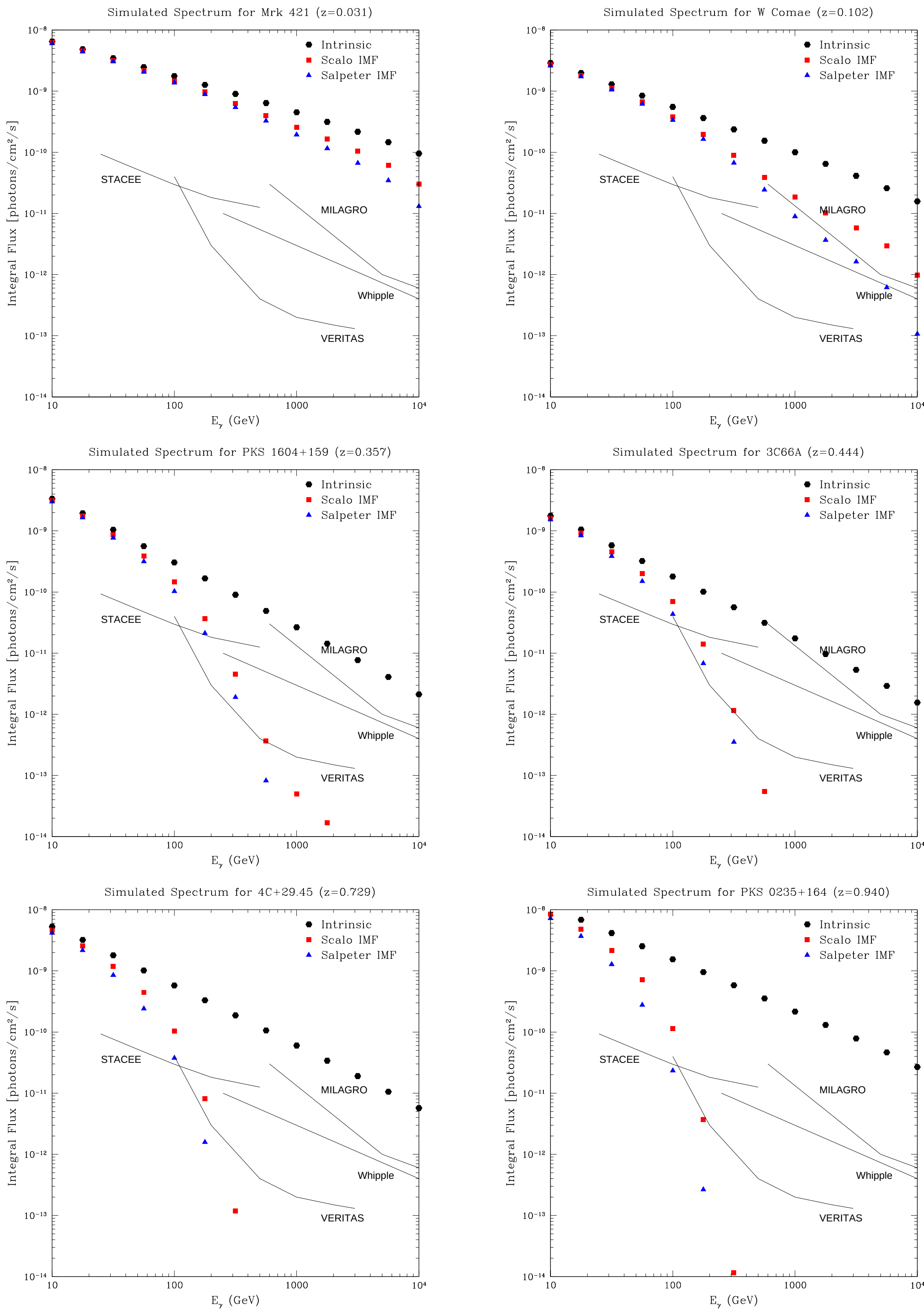

FIGURE 3. Calculation of expected integral flux for six EGRET sources at various redshifts.

of energy for a sample of the red-shifts considered appear in Fig. 2b. The functional form for the simulated differential spectrum is then:

$$\left(\frac{\mathrm{d}\phi}{\mathrm{d}E}\right)_{abs} = \left(\frac{\mathrm{d}\phi}{\mathrm{d}E}\right)_{int} \exp[-\tau(E)] \qquad (1)$$

Integral fluxes were calculated numerically from this absorption corrected differential flux. Results are plotted in Fig. 3 for the two different stellar IMFs under consideration here. Also included for reference on the plots in Fig. 3 are sensitivity curves for a representative sample of ground based gamma ray detectors.

Four of the six sources we considered had been previously selected for observations by the Whipple group [2], and each resulted in a non-detection. These sources are W Comae, PKS 1604+159, 3C66A, and PKS 0235+164. The upper limits placed on the latter three are consistent with our model. However, Whipple's upper limit on W Comae is significantly below both the Scalo and Salpeter corrections to a simple EGRET extrapolated power law spectrum. In addition to this discrepancy for W Comae, we are unable to reproduce Whipple's observed integral flux for Mrk 421 during the same epoch [15]. Comparison of our predicted differential spectrum and the current observed differential spectra from Whipple, HEGRA, and CAT [1,7,10] also yielded disparate results, as illustrated in Fig. 4. The poor correlation between our extrapolated EGRET data and the TeV observations make it clear that we cannot yet make a strong statement about the EBL, or the corresponding IMF, due mainly to the uncertainty of our simple power-law model of the intrinsic source spectrum. In future efforts, we will exchange our simple power law model for a more realistic simulation of the intrinsic source spectrum. However, while the plots in Fig. 3 may not be realistic, they do demonstrate the effects of absorption on the spectrum, and how this feature varies with redshift.

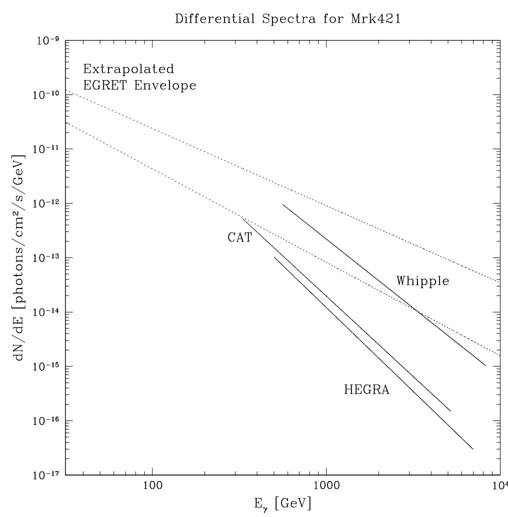

FIGURE 4. TeV spectra for Mrk421 and extrapolated EGRET spectrum.

REFERENCES

1. Aharonian, F. et al., *Astron. & Astrophys.* **350**, 757 (1999).
2. Buckley, J.H., *Astropart. Phys.* **11**, 119 (1999).
3. Bullock, J.S., Ph.D. dissertation, University of California, Santa Cruz (1999).
4. Bullock, J.S. et al., *Astropart. Phys.* **11**, 111 (1999).

5. Gould R.J., Schreder, G.P., *Phys. Rev.* **155**, 1404 (1967).
6. Hartman, R.C. et al., *Astrophys. J.* **123**, 79 (1999).
7. Krennrich, F. et al., *Astrophys. J.* **511**, 149 (1999).
8. MacMinn, D., Primack, J.R., *Space Science Reviews* **75**, 413 (1996).
9. Mukherjee, R. et al., *Proc. 26th ICRC* (Salt Lake City) **3**, 362 (1999).
10. Piron, F. et al., *Proc. 26th ICRC* (Salt Lake City) **3**, 326 (1999).
11. Primack, J.R. et al., *Astropart. Phys.* **11**, 93 (1999).
12. Salamon, M.H., Stecker, F.W., *Astrophys. J.* **493**, 547 (1998).
13. Salpeter, E. *Astrophys. J.* **121**, 61 (1955).
14. Scalo, J.M., *Fund. Cosmic Phys* **11**, 1 (1986).
15. Schubnell, M.S. et al., *Astrophys. J.* **460**, 644 (1996).
16. Somerville, R.S., Primack, J.R., *MNRAS*, in press, astro-ph/9802268 (1999).
17. Thompson, D.J. et al., *Astrophys. J. Supp.* **107**, 227 (1996).